

UV/Optical Emission Accompanying Gamma-ray Burst

Y. Z. Fan^{1,2*} and D. M. Wei^{1,2} [★]

¹Purple Mountain Observatory, Chinese Academy of Science, Nanjing 210008, China

²National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

Accepted Received; in original form

ABSTRACT

We discuss the possible simultaneously UV/optical emission accompanying Gamma-ray bursts (GRBs). We show that as long as the intrinsic spectrum of GRB can extend to ~ 10 GeV or higher, there is a large amount of relativistic e^\pm pairs generated due to the annihilation of the soft γ -rays with the very energetic photons, which dominates over the electrons/positrons associated with the fireball, no matter the fireball is highly magnetized or not (For the highly magnetized fireball, the magnetic field is ordered, the high linear polarization of the multi-wavelength emission is expected). We find that these e^\pm pairs can power an UV flash with $m \simeq 12 - 13$ th magnitude, and the corresponding optical emission can be up to $m_R \simeq 15 - 16$ th magnitude. Such bright UV emission can be detected by the upcoming satellite Swift, planned for launch in 2004. The behavior of the optical-UV spectrum ($F_\nu \propto \nu^{5/2}$) differs significantly from that of the reverse shock emission ($F_\nu \propto \nu^{-\beta/2}$, $\beta \simeq 2.2$), which is a signature of the emission accompanying with GRB. The mild optical emission can be detected with the ROTSE-IIIa telescope system, if the response to the GRB alert is fast enough.

Key words: Gamma-rays: bursts—radiation mechanism: non-thermal

1 INTRODUCTION

Although the central engine for Gamma-ray bursts (GRBs) is far from clear, it is generally suggested that γ -ray bursts are powered by the dissipation of energy in a highly relativistic wind, driven by gravitational collapse of massive star into a neutron star or a black hole (see Mészáros 2002 and Cheng & Lu 2001 for recent reviews). There are two possible models involving this scenario: One is the internal shocks model (Paczynski & Xu 1994; Rees & Mészáros 1994) involving an baryon-rich fireball, which can reproduce the observed temporal structure in GRBs naturally. The other is the Poynting flux driven outflows from magnetized rotators (Usov 1994; Thompson 1994; Mészáros & Rees 1997). Comparing with the widely accepted baryon-rich fireball model, the Poynting flux model is of more and more interest, since: (1) It provides us the most plausible explanation for the very high linear polarization during the prompt γ -ray emission of GRB 021206 (e.g. Coburn & Boggs 2003; Lyutikov, Pariev & Blandford 2003), although some alternative explanations still remain (e.g. Shaviv & Dar 1995; Waxman 2003). (2) Modeling the reverse shock emission of GRB 990123 indicates that the reverse shock region should anchor a strong field far more than the forward shock region holds (Fan et al. 2002; Zhang, Kobayashi & Mészáros 2003), which hints the fireball may

be highly magnetized (see the review of Zhang & Mészáros (2003) for more detail).

In the afterglow epoch, there is few theoretical attentions have been paid on the emission at UV/optical emission during γ -ray burst phase. Pilla & Loeb (1998) have discussed such emission in the internal shocks. However, in their work, the synchrotron self-absorption effect has been ignored (see their figure 3, the spectrum at the optical-UV band takes the form of $F_\nu \propto \nu^{1/3}$). Conversely, before the discovery of the afterglow, this topic is of some interest (e.g., Schaefer et al. 1994; Katz 1994; Wei & Cheng 1997). In this paper, we reinvestigate that topic in some detail. Different from the previous works, here we emphasize the contribution of the e^\pm pairs generated in the phase of γ -burst—as long as the intrinsic spectrum can extend to ~ 10 GeV or higher, there is a large amount of relativistic e^\pm pairs generated due to the annihilation of the soft γ -rays with the energetic photons with energy up to 10 GeV, just as realized by several authors previously (e.g. Pilla & Loeb 1998; Guetta, Spada & Waxman 2001; Mészáros et al. 2002; Li et al. 2003; Fan, Dai & Lu 2004)[†]. There are some evidences that the spectra of some GRBs extend to > 100 MeV (e.g. Schaefer et al. 1998; González et al. 2003; Guetta & Granot 2003). For some GRBs observed by EGRET, a significant fraction

* E-mail: yzfan@pmo.ac.cn(YZF); dmwei@pmo.ac.cn(DMW)

[†] During revising our paper, a great detailed numerical calculation work appeared (Pe'er & Waxman 2003).

of power has been emitted into the GeV energy range, and the spectra can be described by a single power-law ranging from MeV to GeV energy band (See Fishman & Meegan 1995 for a review). We find that those resulting e^\pm pairs power a bright UV flash with $m \simeq 12-13$ th magnitude, the corresponding optical emission can be up to $m_R \simeq 15-16$ th magnitude. Such bright UV emission can be detected by the upcoming Satellite Swift, planned for launch in 2004. The mild optical emission can be detected with the ROTSE-IIIa telescope system, if the response to the GRB alert is fast enough.

This paper is structured as follows: In section 2, we discuss the pair-production and the possibility of annihilation in γ -ray burst phase. In section 3, we calculate the synchrotron radiation of these new born relativistic e^\pm pairs. Conclusions and some discussions on observation are given in section 4.

2 PAIR LOADING IN GRBS

History, a large Lorentz factor $\eta \sim 100-1000$ is first introduced to avoid the “compactness problem” in GRBs. However, a significant fraction of photons with very energetic energy may still suffer from absorption and yielding considerable amount of e^\pm pairs. Pilla & Loeb (1998) have studied spectral signatures of GRB itself by considering pair production and shown there are a large amount of e^\pm pairs generated. The co-moving annihilation time of these pairs is longer than the hydrodynamical time, so they can survive in the wind for a long time. For this reason, Li et al. (2003) have reinvestigated the pair generation in the γ -ray burst phase and studied the reverse shock emission powered by a such pair-rich fireball interacting with the interstellar medium (ISM), and shown there comes the very strong IR flashes. In those two works, the resulting pairs dominate over the electrons associated with baryons. Generally, the typical thermal Lorentz factor of these resulting e^\pm pairs is only several tens, its synchrotron radiation contributes little to the γ -ray band. Consequently, only its inverse Compton (IC) radiation has been calculated (Pilla & Loeb 1998; Fan, Dai & Lu 2004). In this paper we turn to investigate the emission at the much lower energy band, i.e., the UV/optical.

As mentioned early, for the most energetic photons at the high energy end of the spectrum, the optical depth of $\gamma-\gamma$ absorption may exceed unity. As a result, rather than escaping from the outflow, these photons are absorbed by the soft γ -rays and yielding relativistic e^\pm pairs. Below, following Li et al. (2003) and Fan, Dai & Lu (2004), we calculate how many pairs are generated in this process for a pulse with a typical variable timescale $\delta t \sim 0.1$ s (Shen & Song 2003).

An excellent phenomenological fit for the GRB spectrum was introduced by Band et al. (1993), which is characterized by two power laws joined smoothly at a break frequency $\nu_b \approx 1.21 \times 10^{20}$ Hz. For $\nu > \nu_b$, the photon spectra can be approximated by a power law $dN/d\nu = N_{\nu_b}(\nu/\nu_b)^{-(p+2)/2}$, where $N_{\nu_b} = (p-2)(h\nu_b^2)^{-1}L\delta t/2(p-1)$ (Dai & Lu 2002), $p \simeq 2.5$ is the index for a power-law distribution of relativistic electrons/positrons account for the

observed γ -ray emission. Therefore for $\nu > \nu_b$ we have

$$\begin{aligned} N_{>\nu} &= \int_{\nu}^{\infty} (dN/d\nu) d\nu \\ &= [(p-2)/p(p-1)](h\nu_b)^{-1}(\nu/\nu_b)^{-p/2}L\delta t. \end{aligned} \quad (1)$$

A photon with energy $h\nu$ may annihilate any photons above the energy $h\nu_{\text{an}} = (\eta m_e c^2)^2/h\nu$, the optical depth is given by (Lithwick & Sari 2001; Dai & Lu 2002; Li et al. 2003)

$$\tau_{\gamma\gamma}(\nu) = \frac{(11/180)\sigma_T N_{>\nu_{\text{an}}}}{4\pi(\eta^2 c \delta t)^2} \quad (2)$$

A photon with $\tau_{\gamma\gamma}(\nu) > 1$ would be absorbed then deposited in the fireball. The condition $\tau_{\gamma\gamma}(\nu) = 1$ results in $\nu_{\text{an}} \approx 6.4 \times 10^{20}$ Hz $\nu_{b,20.1}^{(p-2)/p} L_{52}^{2/p} \delta t_{-1}^{-2/p} \eta_{2.5}^{-8/p}$ (In this paper, we adopt the convention $Q_x = Q/10^x$ for expressing the physical parameters, using cgs units). The cut off frequency is

$$\nu_{\text{cut}} = 2.2 \times 10^{24} \text{ Hz } \nu_{b,20.1}^{(2-p)/p} L_{52}^{-2/p} \delta t_{-1}^{2/p} \eta_{2.5}^{(2p+8)/p}, \quad (3)$$

the corresponding “thermal” Lorentz factor of resulting e^\pm pairs reads

$$\gamma_{\text{pair,m}} \approx \frac{h\nu_{\text{cut}}}{2\eta m_e c^2} = 29 \nu_{b,20.1}^{(2-p)/p} L_{52}^{-2/p} \delta t_{-1}^{2/p} \eta_{2.5}^{(p+8)/p}. \quad (4)$$

The total number of the resulting e^\pm pairs is

$$\begin{aligned} N_{e^\pm} &= [(p-2)/p(p-1)](h\nu_b)^{-1}(\nu_{\text{cut}}/\nu_b)^{-p/2}L\delta t \\ &= 7.4 \times 10^{50} L_{52}^2 \eta_{2.5}^{-(p+4)} \nu_{b,20.1}^{p-2}. \end{aligned} \quad (5)$$

In principle, more detailed numerical calculation is needed to calculate the number of generating e^\pm pairs just as Pilla & Loeb (1998) and Guetta et al. (2001) have done. However, here we’ll show that our analytical estimation (equation (5)) coincides with the numerical results of Pilla & Loeb (1998) quite well. For the numerical example holding in Pilla & Loeb (1998): $E \approx 10^{51}$ ergs, $M \approx 10^{27}$ g, $\delta t \approx 0.01$ s and $\eta \approx 400$ (where M is the mass of the shell, and other parameters mean as usual). With these values, our equation (5) reads $N'_{e^\pm} \approx 1.14 \times 10^{52} L_{53}^2 \eta_{2.6}^{-(p+4)} \nu_{b,20.1}^{p-2}$. On the other hand, the number of the electron associated with baryons $N'_e = M/m_p \approx 6.0 \times 10^{50}$. The ratio of them is $2N'_{e^\pm}/N'_e \approx 38$. Please note that in the original work of Pilla & Loeb (see the caption of figure 1 (b), astro-ph/97120219), they obtain a ratio of about 40! Such excellent coincidence implies our analytical treatment is reasonable and our results are reliable.

These resulting e^\pm pairs may annihilate each other into γ -ray again. That possibility has been discussed in great detail by Pilla & Loeb (1998), Li et al. (2003) and Fan, Dai & Lu (2004). For typical GRB parameters, $\eta \sim 300$, $\delta t \sim 0.1$ s, $L \sim 10^{52}$ ergs s $^{-1}$, the annihilation time of these pairs is much longer than the hydrodynamic time (measured in the comoving frame). As a result, these new born e^\pm pairs survive in the wind for long time rather than annihilate locally, only for which are our following calculations valid.

3 SYNCHROTRON EMISSION AT THE UV/OPTICAL BAND

The resulting e^\pm pairs are in fast cooling phase, most of them cool down to $\gamma_e \sim 1$ rapidly. However, it is well known

that only the emission of the relativistic electrons/positrons can be described by the synchrotron radiation. For the sub-relativistic electrons, their cyclotron radiation contribute little to the UV/optical emission which is of our interest. Therefore, in this paper, only the electrons with the Lorentz factor $\gamma_e > \gamma_{e,c}$ ($\gamma_{e,c}$ represents a critical Lorentz factor, which plays the same role as the “cooling Lorentz factor” elsewhere) have been taken into account. As an illustration, we take $\gamma_{e,c} = 2$. In the following discussion, the superscripts “ m ” and “ b ” represent the highly magnetized fireball and baryon-rich fireball respectively.

3.1 Baryon-rich Fireball

For a baryon-rich fireball, the number of the total electrons account for the observed γ -ray emission can be estimated by $N_{e,\text{tot}}\eta\gamma_m m_e c^2 = E_\gamma$, γ_m is the typical Lorentz factor of electrons, which is constrained by $\eta\gamma_m^2 eB^b/2\pi m_e c = \nu_b$. B^b is the strength of the co-moving magnetic field, which can be estimated as follows: Assuming $E_B = \epsilon_B E_\gamma$ (E_B being the total magnetic energy carried by the fireball, E_γ being the total energy emitted in the γ -ray band), we have $4\pi(\eta^2 c \delta t)^2 c (B^{b^2}/8\pi)\eta^2 = \epsilon_B L$, which leads to $B^b = 2.9 \times 10^3$ Gauss $L_{52}^{1/2} \eta_{2.5}^{-3} \delta t_{-1}^{-1/2} \epsilon_{B,-1}^{1/2}$. After some simple algebra we have

$$N_{e,\text{tot}} = 5.8 \times 10^{52} E_{\gamma,53} L_{52}^{1/4} \eta_{2.5}^{-2} \delta t_{-1}^{-1/2} \epsilon_{B,-1}^{1/4} \nu_{b,20.1}^{-1/2}. \quad (6)$$

For a typical pulse with typical variable timescale δt , the electrons contained can be estimated as

$$N_e = N_{e,\text{tot}} \delta t / T = 5.8 \times 10^{50} L_{52}^{5/4} \eta_{2.5}^{-2} \delta t_{-1}^{1/2} \epsilon_{B,-1}^{1/4} \nu_{b,20.1}^{-1/2}. \quad (7)$$

where $T \sim 10$ s (measured in the local frame) is the typical “effective” duration of GRBs, within which the lightcurve is relatively smooth and most of the total energy has been emitted. Thus $L \approx E_\gamma / T$. Now we can define a coefficient k_\pm as

$$k_\pm \equiv N_{e\pm} / N_e = 1.3 L_{52}^{3/4} \eta_{2.5}^{-(p+2)} \nu_{b,20.1}^{p-3/2} \delta t_{-1}^{-1/2} \epsilon_{B,-1}^{-1/4}. \quad (8)$$

With equation (4), the characteristic synchrotron emission frequency of the new born e^\pm can be estimated by

$$\begin{aligned} \nu_m^b &= \eta\gamma_{\text{pair},m}^2 \frac{eB^b}{2\pi m_e c} \\ &\approx 2.0 \times 10^{15} \text{ Hz } \epsilon_{B,-1}^{\frac{1}{2}} \eta_{2.5}^{\frac{2(2-p)}{p}} \nu_{b,20.1}^{\frac{(p-8)}{2p}} L_{52}^{\frac{(4-p)}{2p}} \delta t_{-1}^{\frac{16}{p}} \eta_{2.5}^{\frac{16}{p}}. \end{aligned} \quad (9)$$

where m_e being the mass of the electron.

The electron with a Lorentz factor $\gamma_e (\gg \gamma_{e,c})$ cools down to $\gamma_{e,c}$ at a timescale

$$t_{\text{life}}^b \approx 3\pi m_e c / \sigma_T B^{b^2} \eta \gamma_{e,c} \approx 0.076 \text{ s } \epsilon_{B,-1}^{-1} L_{52}^{-1} \eta_{2.5}^5 \delta t_{-1}^2. \quad (10)$$

which is comparable with δt . The characteristic frequency with respect to $\gamma_{e,c}$ is

$$\nu_c^b = \eta\gamma_{e,c}^2 \frac{eB^b}{2\pi m_e c} \approx 9.8 \times 10^{12} \text{ Hz } \epsilon_{B,-1}^{1/2} L_{52}^{1/2} \eta_{2.5}^{-2} \delta t_{-1}^{-1}. \quad (11)$$

To calculate the observed energy flux, the synchrotron self-absorption effect must be considered. Now, the electrons/positrons can be classed into two components: one is the electrons account for the γ -ray emission with the distribution $dn/d\gamma_e \propto \gamma_e^{-2}$ for $\gamma_{e,c} < \gamma_e < \gamma_m$ and $dn/d\gamma_e \propto \gamma_e^{-(p+1)}$ for $\gamma_e > \gamma_m$. The other is the resulting e^\pm pairs with the distribution $dn/d\gamma_e \propto \gamma_e^{-2}$ for

$\gamma_{e,c} < \gamma_e < \gamma_{\text{pair},m}$ and $dn/d\gamma_e \propto \gamma_e^{-(p+4)/2}$ for $\gamma_e > \gamma_{\text{pair},m}$. For the former, the synchrotron self-absorption frequency can be estimated by (see the Appendix of Wu et al. 2003 for detail): $\nu_a = 2.4 \times 10^{15} \text{ Hz } L_{52}^{3/4} \eta_{2.5}^{-3} \delta t_{-1}^{-7/6} \epsilon_{B,-1}^{5/12} \nu_{b,20.1}^{-1/6}$. For the latter, the synchrotron self-absorption frequency can be estimated by (Wu et al. 2003): $\nu'_a = 4.0 \times 10^{15} \text{ Hz } [\epsilon_{B,-1}^{p/2} \eta_{2.5}^{-4(p+2)} \delta t_{-1}^{-(p+8)} L_{52}^{(8+p)/2} \nu_{b,20.1}^{2(p-2)}]^{1/(p+12)}$. In practice, the self-absorption frequency of such a system is determined by these two components corporately rather than separately. Here, as a rough estimation, we assume the actual self-absorption frequency is about k ($\simeq 1 + O(0.1)$) times ν'_a , therefore

$$\begin{aligned} \nu_a^b &= 4.0 \times 10^{15} \text{ Hz } k [\epsilon_{B,-1}^{p/2} \eta_{2.5}^{-4(p+2)} \\ &\delta t_{-1}^{-(p+8)} L_{52}^{(8+p)/2} \nu_{b,20.1}^{2(p-2)}]^{1/(p+12)} \end{aligned} \quad (12)$$

Please note that ν_m^b , ν_c^b and ν_a^b are all measured in the local frame. As translating into the observer frame, all of them need to be multiplied by $1/(1+z)$, $z \sim 1$ being the typical redshift of GRBs. The peak flux can be estimated by

$$\begin{aligned} F_{\nu_a}^b &= F_{\nu_{\text{max}}}^b \left(\frac{\nu_m^b}{\nu_c^b} \right)^{-1/2} \left(\frac{\nu_a^b}{\nu_m^b} \right)^{-(p+2)/4} \\ &= 0.144 \text{ Jy } \epsilon_{B,-1}^{\frac{p-3}{p+12}} k^{-(p+2)/4} \left(\frac{1+1/2k_\pm}{1.38} \right)^{\frac{2(14-3p)}{p+12}} \\ &\delta t_{-1}^{\frac{10}{p+12}} L_{52}^{\frac{p+7}{p+12}} \nu_b^{\frac{5(p-2)}{p+12}} \left(\frac{1+z}{2} \right) D_{L,28.34}^{-2}. \end{aligned} \quad (13)$$

where $F_{\nu_{\text{max}}}^b = N_{\text{rad}}^b \eta P_{\nu_m}^b (1+z)/4\pi D_L^2$, $N_{\text{rad}}^b = 2N_{e\pm} (1 + \frac{1}{2k_\pm}) t_{\text{life}}^b / \delta t$, $P_{\nu_m}^b = e^3 B^b / m_e c^2$. D_L is the luminosity distance of the source (we take $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$).

Since $\nu_c^b < \nu_{R,\text{obs}} = 5 \times 10^{14} \text{ Hz} < \nu_m^b < \nu_a^b$, the observed R band flux can be estimated by

$$\begin{aligned} F_{\nu_{R,\text{obs}}}^b &= F_{\nu_a}^b \left[\frac{(1+z)\nu_{R,\text{obs}}}{\nu_a^b} \right]^{5/2} \\ &= 4.5 \text{ mJy } k^{-(p+12)/4} [(1+1/2k_\pm)/1.38] \\ &\left(\frac{1+z}{2} \right)^{7/2} D_{L,28.34}^{-2} \epsilon_{B,-1}^{-1/4} L_{52}^{-1/4} \eta_{2.5}^4 \delta t_{-1}^{5/2}. \end{aligned} \quad (14)$$

which hints for typical parameters, the optical emission is weak to $m_R \approx 15$.

Similarly, for $\nu_{\text{obs}} = 1.8 \times 10^{15} \text{ Hz}$ corresponding to the wavelength $\lambda = 170 \text{ nm}$, the upper limit of UVOT carried by Swift (see in <http://swift.gsfc.nasa.gov>), the predicted emission is high up to $m \simeq 12$ th magnitude.

Pe’er & Waxman (2003) have calculated the prompt GRB spectra ($> 0.1 \text{ keV}$) in great detail within the fireball model framework, and some important effects such as the e^\pm pairs production/annihilation and so on have been taken into account. In order to estimate the validity of our calculation, we compare our results with the detailed numerical calculation (Pe’er & Waxman 2003), and find that our results do not show much difference from theirs. For example, for their low compactness case shown in their figure 4: $L = 10^{52} \text{ ergs}$, $\epsilon_e = \epsilon_B = 10^{-0.5}$, $p = 3$, $\delta t = 0.01 \text{ s}$ and $\eta = 300$. The flux $F_{\nu_{R,\text{obs}}} \sim 5 \times 10^{-5} \text{ Jy}$ (we have extended their figure to $h\nu_{R,\text{obs}} \approx 2 \text{ eV}$ energy range, at which energy band $F_\nu \propto \nu^{5/2}$). With these parameters, our simple analytic result (see Eq. (14)) gives $F_{\nu_{R,\text{obs}}} \sim 1.4 \times 10^{-5} \text{ Jy}$. Therefore, as an approximation, we think our analytic re-

sults can be used to estimate the UV/Optical emission from GRBs.

Below we discuss the possible SSC (synchrotron self-Compton) radiation briefly. The typical energy of the SSC radiation can be estimated by $h\nu_m^{\text{SSC}} \simeq 2\gamma_{\text{pair,m}}^2 h\nu_m \approx 18$ keV. The ratio of the SSC luminosity (L_{SSC}) to the synchrotron luminosity (L_{syn}) of e^\pm pairs can be estimated by $x \equiv \frac{L_{\text{SSC}}}{L_{\text{syn}}} = \frac{U_e/(1+x)}{U_B}$, where U_e/U_B are the electron/magnetic energy density respectively. Hence $x = (-1 + \sqrt{1 + 4U_e/U_B})/2 = (-1 + \sqrt{1 + 4E_{\gamma,\nu>\nu_{\text{cut}}}/\epsilon_B E_\gamma})/2 \sim 0.6$ for $\epsilon_B \simeq 0.1$. $L_{\text{syn}}/L \approx E_{\gamma,\nu>\nu_{\text{cut}}}/[(1+x)E_\gamma] \approx (\nu_{\text{cut}}/\nu_b)^{(2-p)/2}/(1+x)$. Therefore $L_{\text{SSC}}/L \approx x(\nu_{\text{cut}}/\nu_b)^{(2-p)/2}/(1+x) \approx 0.04$. So the SSC component can change the observed soft γ -ray spectrum in some degree, which may help to explain the observed X-ray excess in some GRBs (Band et al. 1993).

3.2 Highly Magnetized Fireball

For the highly magnetized fireball, the characteristic synchrotron emission frequency of the new born e^\pm pairs can be estimated by

$$\nu_m^{\text{m}} = \eta\gamma_{\text{pair,m}}^2 \frac{eB^{\text{m}}}{2\pi m_e c} \approx 4.4 \times 10^{15} \text{ Hz } \epsilon^{\frac{1}{2}} \nu_{b,20.1}^{\frac{2(2-p)}{p}} L_{52}^{\frac{(p-8)}{2p}} \delta t_{-1}^{\frac{(4-p)}{p}} \eta_{2.5}^{\frac{16}{p}}. \quad (15)$$

At the present case, we assume the electromagnetic energy dominated over other ones, thus B^{m} can be estimated by $B^{\text{m}} \approx 6.3 \times 10^3 \text{ Gauss } \epsilon^{1/2} L_{52}^{1/2} \eta_{2.5}^{-3} \delta t_{-1}^{-1}$, $\epsilon = E_B/E_\gamma \sim 1$.

Now, the electron with a Lorentz factor γ_e ($\gg \gamma_{e,c}$) cools down to $\gamma_{e,c}$ at a timescale

$$t_{\text{life}}^{\text{m}} \approx 3\pi m_e c / \sigma_T B^{\text{m}2} \eta \gamma_{e,c} \approx 0.016 \text{ s } \epsilon^{-1} L_{52}^{-1} \eta_{2.5}^5 \delta t_{-1}^2. \quad (16)$$

The characteristic frequency with respect to $\gamma_{e,c}$ is

$$\nu_c^{\text{m}} = \eta\gamma_{e,c}^2 \frac{eB^{\text{m}}}{2\pi m_e c} \approx 2.1 \times 10^{13} \text{ Hz } \epsilon^{1/2} L_{52}^{1/2} \eta_{2.5}^{-2} \delta t_{-1}^{-1}. \quad (17)$$

The synchrotron self-absorption frequency ($\nu_a > \nu_m$) can be estimated by (Wu et al. 2003)

$$\nu_a^{\text{m}} = 5.6 \times 10^{15} \text{ Hz } [\epsilon^{p/2} \eta_{2.5}^{-4(p+2)} \delta t_{-1}^{-(p+8)} L_{52}^{(8+p)/2} \nu_{b,20.1}^{2(p-2)/1/(p+12)}]. \quad (18)$$

where it is assumed that the electrons/positrons carried by the fireball is far less than the e^\pm pairs generated in the γ -ray phase (Zhang & Mészáros 2002). Now the peak flux can be estimated by

$$F_{\nu_a}^{\text{m}} = F_{\nu_{\text{max}}}^{\text{m}} \left(\frac{\nu_m^{\text{m}}}{\nu_c^{\text{m}}}\right)^{-1/2} \left(\frac{\nu_a^{\text{m}}}{\nu_m^{\text{m}}}\right)^{-(p+2)/4} = 0.096 \text{ Jy } \epsilon^{\frac{p-3}{p+12}} \eta_{2.5}^{\frac{2(14-3p)}{p+12}} \delta t_{-1}^{\frac{10}{p+12}} L_{52}^{\frac{p+7}{p+12}} \nu_b^{\frac{5(p-2)}{p+12}} \left(\frac{1+z}{2}\right) D_{L,28.34}^{-2}. \quad (19)$$

where $F_{\nu_{\text{max}}}^{\text{m}} = N_{\text{rad}}^{\text{m}} \eta P_{\nu_m}^{\text{m}} (1+z)/4\pi D_L^2$, $N_{\text{rad}}^{\text{m}} = 2N_{e^\pm} t_{\text{life}}^{\text{m}}/\delta t$, $P_{\nu_m}^{\text{m}} = e^3 B^{\text{m}}/m_e c^2$.

The observed R band flux can be estimated by

$$F_{\nu_{R,\text{obs}}}^{\text{m}} = F_{\nu_a}^{\text{m}} \left[\frac{(1+z)\nu_{R,\text{obs}}}{\nu_a^{\text{m}}}\right]^{5/2} = 1.4 \text{ mJy } \left(\frac{1+z}{2}\right)^{7/2} D_{L,28.34}^{-2} \epsilon^{-1/4}$$

$$L_{52}^{-1/4} \eta_{2.5}^4 \delta t_{-1}^{5/2}. \quad (20)$$

which hints for typical parameters, the optical emission is weak to $m_R \approx 16$.

Similarly, for $\nu_{\text{obs}} = 1.8 \times 10^{15} \text{ Hz}$, the predicted emission is up to $m \simeq 13$ th magnitude.

In the present case, the typical energy of the SSC radiation can be estimated by $h\nu_m^{\text{SSC}} \simeq 2\gamma_{\text{pair,m}}^2 h\nu_m \approx 35 \text{ keV}$. Now, $x = (-1 + \sqrt{1 + 4U_e/U_B})/2 = (-1 + \sqrt{1 + 4E_{\gamma,\nu>\nu_{\text{cut}}}/\epsilon E_\gamma})/2 \approx E_{\gamma,\nu>\nu_{\text{cut}}}/\epsilon E_\gamma$ for $E_{\gamma,\nu>\nu_{\text{cut}}} \ll \epsilon E_\gamma$. Thus $L_{\text{SSC}}/L \approx 1/[(1+x)\epsilon(\nu_{\text{cut}}/\nu_b)^{(p-2)}] \approx 0.01\epsilon^{-1}$, which implies that the SSC component can not change the observed soft γ -ray spectrum significantly, at least for the typical parameters taken here.

4 DISCUSSION AND CONCLUSIONS

GRBs are characterized by emission in the few hundred keV ranges with a non-thermal spectrum, X-ray emission is weaker—only a few percent of the energy is emitted below 10 keV and prompt emission at lower energies has not been observed so far. One exception is the optical flash accompanying with GRB 990123 (Akerlof et al. 1999), which is believed to be powered by the reverse shock (Sari & Piran 1999). If such emission is the low-energy tail of the γ -ray emission, the light curves in the different energy bands should be highly correlated, which is not the case (Sari & Piran 1999). Akerlof et al. (2000) have performed a search for optical counterparts to six GRBs with location errors of 1 square degree or better, but no optical counterpart has been detected, the earliest limiting sensitivity is $m > 13.1$ at 10.85 seconds after the gamma-ray rises. No simultaneous optical emission from GRBs has been detected by Kehoe et al. (2001), too. All of these observations suggest that the simultaneous optical emission should not be typically brighter than 14th magnitude, which coincides with our results presented here.

The typical prompt optical emission predicted in this paper, $m_R \sim 15 - 16$ th magnitude, is significantly stronger than $m_V \sim 18$ th magnitude predicted by Katz (1994). Such emission can be detected by the current ROTSE-IIIa telescope system, which is a 0.45-m robotic reflecting telescope and managed by a fully-automated system of interacting daemons within a Linux environment. The telescope has an f-ratio of 1.9, yielding a field of view of 1.8×1.8 degrees. The control system is connected via a TCP/IP socket to the Gamma-ray Burst Coordinate Network (GCN), which can respond to GRB alerts fast enough (< 10 s). ROSTE-IIIa can reach 17th magnitude in a 5-s exposure, 17.5 in 20-s exposure (see Smith et al. 2003 for detail), which is sufficient to detect the optical emission predicted in this paper. However, for the standard fireball model, the very early optical emission powered by the reverse shock can be up to $m_R \sim 9$ th magnitude or even brighter (Sari & Piran 1999; Wu et al. 2003; Li et al. 2003), which far surpass the optical emission predicted here. In practice, such strong early optical emission should be very rare, since it has not been detected for most GRBs (Akerlof et al 2000; Kehoe et al. 2001). It is unclear why the early optical emission is so weak. If the fireball is highly magnetized, such emission may be weak to $m_R \sim 14$ th magnitude at the deceleration radius $R_{\text{dec}} \sim 10^{17} \text{ cm}$, the corresponding timescale

$t_{\text{obs}} \sim 20 \text{ s} (1+z) R_{\text{dec}, 17\eta_{2.5}^{-2}}$ (Fan, Wei & Wang 2004). In the collision model of the magnetized wind and the external medium proposed by Smolsky & Usov (2000), the synchrotron radiation generated in the vicinity of the wind front can be high up to tens of MeV, rather than eV as we generally suggested. In this case, the very early optical afterglow is very weak. So, the optical emission accompanying with GRB may be detected independently.

Due to the strong synchrotron self-absorption, the emission peaks at UV band. For $\nu_{\text{obs}} = 1.8 \times 10^{15} \text{ Hz}$ ($\lambda = 170 \text{ nm}$), the typically simultaneous emission is high up to $m \simeq 12 - 13$ th magnitude, which is bright enough to be detected by the UVOT (covering $170 \text{ nm} - 650 \text{ nm}$ with 6 colors) carried by Swift, planned for launch in early 2004. The observation of that UV emission is important, since: at UV band, the spectrum predicted in this paper takes the form of $F_{\nu} \propto \nu^{5/2}$, which is significantly different from that of the reverse shock emission, $F_{\nu} \propto \nu^{-\beta/2}$, where $\beta \simeq 2.2$ is the index of the power-law distribution of the relativistic electrons heated by the reverse shock (Sari & Piran 1999; Fan et al. 2002; Wu et al. 2003). The flux of UV emission predicted here is far above that of the optical emission, it is quite the contrary for the reverse shock emission. Therefore, the spectrum feature at the optical-UV band ($F_{\nu} \propto \nu^{5/2}$) is a signature of the emission accompanying GRBs.

For both the baryon-rich fireball and highly magnetized one, the generated e^{\pm} pairs dominated over the electrons (including positrons) associated with the fireball. For reproducing the observed γ -ray emission, the magnetic field strengthens for these two type fireballs are comparable. Consequently, the UV/optical emission predicted here do not show much difference for these two kinds of fireballs. However, for the highly magnetized fireball, the magnetic field is ordered, so the high linear polarization of the synchrotron radiation at multi-wavelength bands is expected.

Pilla & Loeb (1998) have discussed the possible IC scattering of the resulting e^{\pm} pairs with the intrinsic GRB photons, and found that if $U_{\gamma} \gg U_{\text{m}}$, the pairs transfer nearly all of their energy back to the radiation field via IC scattering. Fortunately, for the two cases discussed here, U_{γ} and U_{m} are comparable, so that IC process may be important but is not dominant, especially for the highly magnetized fireball. Therefore it will not change our result presented here significantly (The detailed numerical research is beyond the scope of this Paper).

It should be noted that in this paper our results are based on the simple analytic analysis, which is a great simplification of the real situation. In our calculation, some important effects such as the pair annihilation have not been taken into account. However, as described in previous section, we found that our results are not much different from those of detailed numerical calculations (e.g., Pilla & Loeb 1998; pe'er & waxman 2003). This suggests that as an order estimation, our present work is reliable. Furthermore, our work has the benefit of showing scalings with parameters better. We have shown that the predicted flux in the UV/Optical band accompanying GRBs strongly depends on the typical variability timescale (δt) as well as the typical bulk Lorentz factor (η), i.e., $F \propto \eta^4 \delta t^{5/2}$. In our calculation, we take the value $\delta t \sim 0.1 \text{ s}$ based on the analysis of the BATSE bursts (Shen & Song 2003). In lots of other works, δt is assumed to be low to millisecond or even shorter. If that is

the case, then the UV/Optical emission predicted here will be much dimmer unless the Lorentz factor is much larger. Therefore, the further UVOT observation can provide the good chance to test our predictions or impose some important constraints on the poor known parameters of GRBs.

ACKNOWLEDGMENTS

Y. Z. Fan thanks Drs. D. Guetta, Z. Li and X. F. Wu for their kind help. We also thank T. Lu, Z. G. Dai, Y. F. Huang and X. Y. Wang for valuable comments. We appreciate the anonymous referees for their useful suggestions that enable us to improve the paper significantly. This work was supported by the National Natural Science Foundation of China (grants 10073022, 10225314 and 10233010), the National 973 Project (NKBRFSF G19990754).

REFERENCES

- Akerlof C. et al., 1999, *Nat*, 398, 400
- Akerlof C. et al., 2000, *ApJ*, 532, L25
- Band D. et al., 1993, *ApJ*, 413, 281
- Cheng K. S., Lu T., 2001, *Chin. J. Astron. Astrophys.*, 1, 1
- Coburn W., Boggs S. E., 2003, *Nat*, 423, 415
- Dai Z. G., Lu T., 2002, *ApJ*, 580, 1013
- Fan Y. Z., Dai Z. G., Huang Y. F., Lu T., 2002, *Chin. J. Astron. Astrophys.*, 2, 449
- Fan Y. Z., Dai Z. G., Lu T., 2004a, *Acta. Astron. Sinica*, 45, 25
- Fan Y. Z., Wei D. M., Wang C. F., 2004b, *A&A*, 424, 477
- Fishman G. J., Meegan C. A., 1995, *ARA&A*, 33, 415
- Gonzalez M. M., Dingus B. L., Kaneko Y., Preece R. D., Dermer C. D., Briggs M. S., 2003, *Nat*, 424, 14
- Guetta D., Granot J., 2003, *ApJ*, 585, 885
- Guetta D., Spada M., Waxman E., 2001, *ApJ*, 557, 399
- Katz J. Z., 1994, *ApJ*, 432, L107
- Kehoe R. et al., 2001, *ApJ*, 554, L159
- Li Z., Dai Z. G., Lu T., Song L. M., 2003, *ApJ*, 599, 380
- Lithwick Y., Sari R., 2001, *ApJ*, 555, 540
- Lyutikov M., Pariev V. I., Blanford R. D., 2003, *ApJ*, 597, 998
- Mészáros P., 2002, *ARA&A*, 40, 137
- Mészáros P., Ramirez-Ruiz E., Rees M. J., Zhang B., 2002, *ApJ*, 578, 812
- Mészáros P., Rees M. J., 1997, *ApJ*, 482, L29
- Paczynski B., Xu G. H., 1994, *ApJ*, 427, 708
- Pe'er A., Waxman E., 2003, *ApJ*, submitted (astro-ph/ 0311252)
- Pilla R., Loeb A., 1998, *ApJ*, 494, L167
- Rees M. J., Mészáros P., 1994, *ApJ*, 430, L93
- Sari R., Piran T., 1999, *ApJ*, 517, L109
- Schaefer B. E. et al., 1994, *ApJ*, 422, L71
- Schaefer B. E. et al., 1998, *ApJ*, 492, 696
- Shaviv N. J., Dar A., 1995, *ApJ*, 447, 863
- Shen R. F., Song L. M., 2003, *PASJ*, 55, 345
- Smith D. et al., 2003, *AAS*, 202, 4602
- Smolsky M. V., Usov V. V., 2000, *ApJ*, 537, 764
- Thompson C., 1994, *MNRAS*, 270, 480
- Usov V. V., 1994, *MNRAS*, 267, 1035
- Waxman E. 2003, *Nat*, 423, 388
- Wei D. M., Cheng K. S., 1997, *MNRAS*, 290, 107
- Wu X. F., Dai Z. G., Huang Y. F., Lu T., 2003, *MNRAS*, 342, 1131
- Zhang B., Kobayashi S., Mészáros P., 2003, *ApJ*, 595, 950
- Zhang B., Mészáros P., 2002, *ApJ*, 581, 1236
- Zhang B., & Mészáros P., 2003, *Int. J. Mod. Phys. A*, 19, 2385